Comité de Estudio A1 - Máquinas Eléctricas Rotativas

FATIGUE ASSESSMENT ON HYDRO GENERATOR POLE FIXATION

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Summary *– Recent studies and prototype experience raised concerns about geometries conventionally used for pole fixation. As a leading supplier of hydro power technology the company has been paying high attention to this issue for years. A procedure for risk assessment with respect to fatigue and resulting damage has been established. This procedure utilizes FEA calculations and a fatigue evaluation based on an internationally recognized FKM-Guideline. The procedure may be used prior to any Non-Destructive Testing (NDT) inspection to assess the condition of a machine. Following our experience, the paper illustrates the assessment process and its variations, viable solutions, the execution of the chosen solution on the example of the rotor pole fixation, a major generator component.*

Keywords: Fatigue – Hydro-generators – Poles – Pole Fixation

1 Motivation

In the hydro industry, the expected lifetime for electrical components of hydro generators is in the range of 30 to 40 years, e.g. for a winding replacement. But it is not the number of years that defines the end of design life of the mechanical parts; it is the number of load cycles a component has been subject to. With a changing number of load cycles like start/stops per day or year due to e. g. changing grid requirements, the number of years of lifetime can reduce much faster than originally expected. As many power plants operate longer than 30 or 40 years, the re-assessment of the mechanical design life is becoming a more and more important factor for units that are in operation for several decades. Next to the static strength assessment, the fatigue assessment plays a major part in the evaluation of the unit condition. With a static strength assessment the maximum static load on the components is assessed. All components have to withstand this maximum static load. During the fatigue assessment the dynamically acting loads are evaluated considering a certain load spectrum. The load spectrum is the sum of different load conditions of the generator like start/stops, load rejections or runaway events. Today, more sophisticated and detailed methods are available to determine the design life of a generator and therefore also for a crucial component like the rotor pole fixation.

The result of a fatigue assessment is the allowed load spectrum for an electrical machine before a loss of the machines integrity can occur. Hence a re-assessment of the design life allows operators to better understand the remaining life time of their electrical machines and to plan inspection and maintenance intervals and if required component replacements. In case the number of actual cycles exceeds the allowed number, further steps are recommended and different solutions can be investigated to allow further operation of the machine.

1.1 Static and fatigue strength assessment

Strength assessments for life time evaluation are a complex issue and several methods have been proposed over the years. Different assessment methods are used worldwide for different applications in the mechanical industry for static and fatigue strength assessment. Well known methodologies are ASME-Code or the FKM-Guideline [1].

For the static strength assessment the evaluation of nominal stresses is generally used. For the fatigue assessment comparative studies for different assessment methods and standards were carried out. The results of the analytical fatigue strength assessment of several electrical machines were compared with the results of non-destructive testing (NDT) of the rotor pole fixation. The best congruence was found with the assessment based on the FKM-Guideline, an internationally recognized guideline that was elaborated by a group of German experts with support of the Forschungskuratorium Maschinenbau.

The FKM-Guideline describes the method for static and fatigue strength assessment based on local or nominal stresses for components made of steel, cast iron and aluminum materials. The FKM-Guideline is available since 1994. Different standards are considered in the guideline from earlier decades and a continuous improvement of the guideline is ensured.

The chapter for fatigue strength assessment with local stresses was adopted. For the assessment a synthetic stress-cycle curve (SN-Curve) with a survival probability of 97.5% is derived from a statistical-empirical database. Due to the statistical background, the FKM-Guideline proposes a material safety factor that depends on regular inspections and consequences of a component failure.

Typically the complete proof of structural integrity contains both static and fatigue analysis. This paper focuses fatigue analysis.

2 Main steps for the fatigue strength assessment

Fig. 1 shows the main steps for a fatigue assessment. Different specific inputs are required for the calculations. With the projects boundary conditions, the material properties and the rotational speeds of the generator, the local stresses are determined by FEA. The calculated stresses can then be assessed based on the FKM-Guideline.

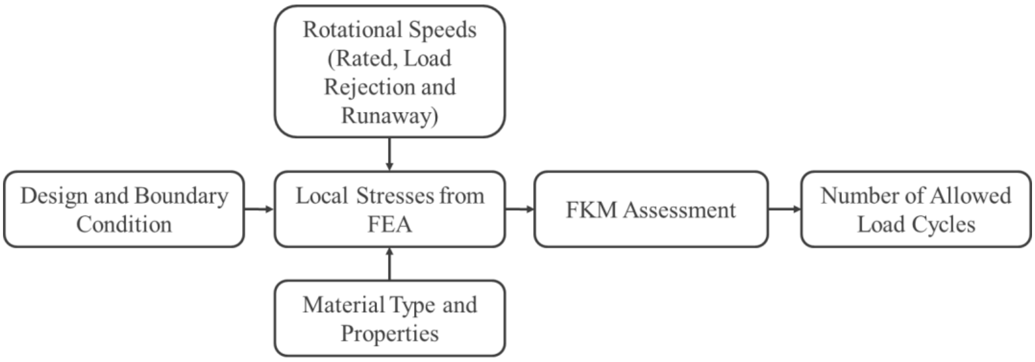


Fig. 1: Main steps of fatigue assessment

The result of the assessment is the allowed load spectrum until a crack initiates. It shall be noted that the results cannot be transferred from one unit to other units, as each unit’s own design and boundary conditions have to be taken into account to determine its number of allowed cycles.

2.1 Stress evaluation based on FEA

The assessment starts with the detailed analysis of the stresses in the component for different operational conditions, which are nominal speed, speed reached after a load rejection and runaway speed. The stress evaluation for the pole fixation is performed by means of FEA under consideration of the original geometry, material properties and boundary conditions. The geometry is usually taken from the component drawings, but can also be determined during a site assessment if no drawings are available.

The FEA can be performed for a 2D or 3D model. The 2D CAD model represents one axial section of the pole and cannot directly consider axial influences. For the 3D CAD model the complete pole is modelled with the respective axial length and geometry. The time to perform a 2D FEA is approximately only a third of the time required for a 3D FEA.

As a screening step a 2D linear elastic FEA for the highest loaded axial section provides quick and sufficiently precise results. The 2D FEA has been calibrated with several 3D FEA studies of representative geometries.

The highest loaded axial section is usually the pole endplate region. The pole endplate is subject to higher load due to the rotor winding overhang (see Fig. 2).

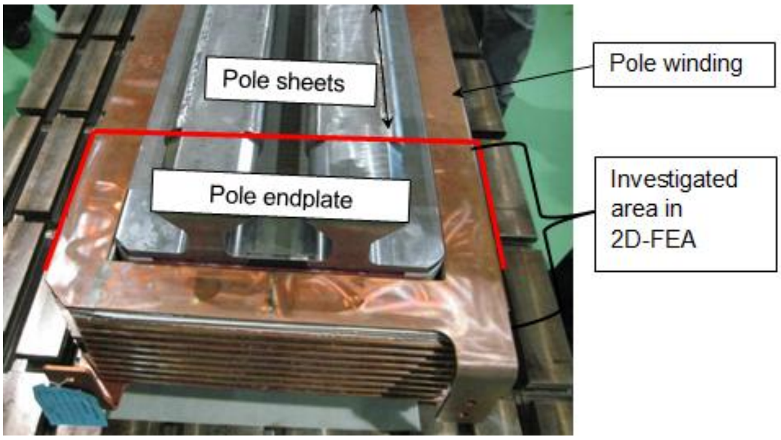


Fig. 2: Typical rotor pole endplate section

Nevertheless, if the results of the 2D analysis produce marginal assessment results with regards to remaining life expectancy or special pole or rim designs, a 3D analysis is necessary in order to take the project's characteristics into consideration.

The 3D-FEA calculations were adapted during the last years with results from various hydro-electrical machines. Several experimental tests on prototypes were necessary to describe well enough the mechanical properties of the pole and rotor.

2.2 Fatigue assessment based on FKM-Guideline

The calculated linear elastic stresses of the FEA will be assessed with an adapted synthetic SN-Curve based on the FKM-Guideline adjusted to material, design, and load of each project.

For the adaption, the material type like rolled, forged or cast steel and the typical material properties like yield point, ultimate strength and the elongation of break are important. If material certificates are available, the tested material properties are considered for the re-assessment. If no data is available, there is a possibility to define the material properties by specific tests during a site assessment. For example, samples can be removed from the components for a tensile test. A hardness test is recommended to confirm the material properties.

In close collaboration with universities worldwide, fatigue tests were carried out allowing to adapt or at least to confirm the assumptions of the FKM-Guideline by experimental tests for the specific components and materials.

As result the assessment offers the allowable number of cycles until a crack eventually initiates.

3 Result evaluation and subsequent steps

To evaluate the fatigue assessment results of an existing pole fixation, to the actual load spectrum is compared to the allowable load spectrum (Fig. 3). To the owner this will provide valuable information for the assessment of the risk situation of the respective generator or motor generator.

Fig. 3 Comparison of allowed and actual number of load cycles

A NDT inspection is recommended once the actual load spectrum exceeds the maximum allowed load spectrum. It is suggested to consider an inspection in certain cases e.g. unit is already in operation for more than 30 years. In the other cases, the result can be used to define the upcoming inspection interval for the rotor pole fixation.

3.1 Inspection method

Different NDT methods are available to inspect mechanical parts of a generator. Together with PWT (Prüf- und Werkstoffstechnik), a testing laboratory in Germany, the company developed an adapted magnetic particle (MT) inspection method especially for the rotor components, as not every NDT method can be used for the concerned pole fixation area. For example, penetrant testing (PT) will show every gap between pole or rotor rim sheets as an indication. With this method a crack cannot be determined safely. The application of the MT testing showed early that it cannot be performed conform to any national or international standard for MT inspections.

If a linear indication is found during inspection, grinding can determine if it is a crack and its possible depth. This is an iterative process: After grinding of 0.5 to 1 mm, the NDT inspection is repeated. The iteration is continued until no further indication is found. The final crack depth is determined with a rubber cast. Soft rubber is pushed in the grinded area and after the curing, the image can be measured. Otherwise a print case can be used created by a laser. A 3D model can be created from this tracking to account for the material excavation in the FEA model for further calculations.

3.2 Possible solutions after inspection of the pole fixation

After the NDT the condition of the generator pole fixation is known. Next steps can be taken to bring the machine back in operation with an acceptable inspection interval. During the last years different solutions for further operation have been developed and executed. There are two main scenarios (Fig. 4):

- the generator is in a good condition without any indications or
- the generator is showing indications.

The elaboration of scenarios regarding possible operation, repair or replacement solutions ahead of an inspection is highly recommended. This allows that next steps can be decided immediately when the results of the inspection are available and the outage time of the unit is reduced to a minimum.

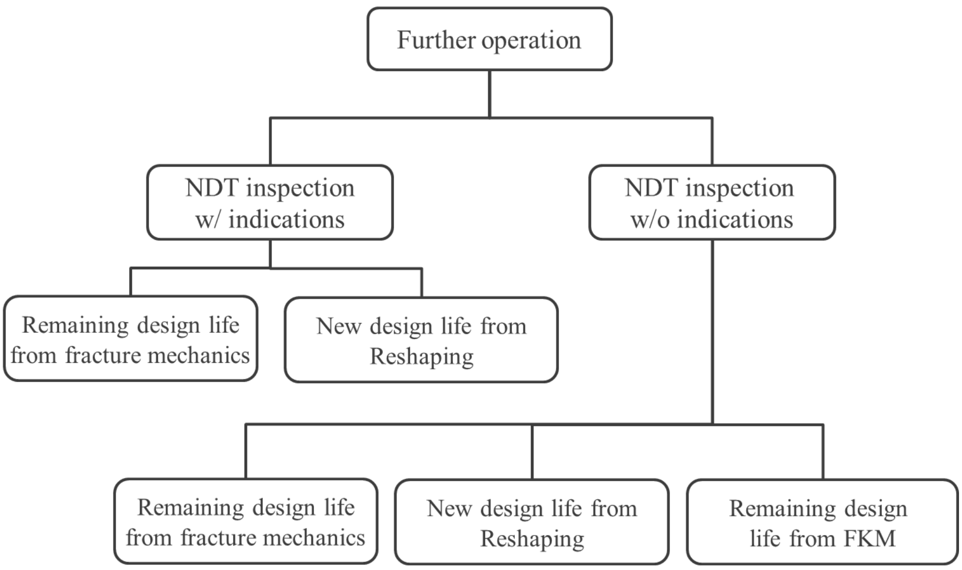


Fig. 4: Different possibilities for further operation

3.2.1 Inspection with indications

Mainly two solutions are possible:

- Reshaping (see Chapter 3.3). The new inspection interval is determined by the FKM-Guideline fatigue assessment of the new geometry.
- Fracture mechanic analysis, if a reshaping is not applicable. See Chapter 3.4.

3.2.2 Inspection without indications

In this case, the generator can go back in operation without any modification, if the number of cycles of the generator has not reached the maximum allowable load spectrum from the FKM-Guideline fatigue assessment yet. The next inspection is recommended when the maximum allowable load spectrum is reached.
If the maximum allowable load spectrum is already consumed, the same methods apply as if indications are found. The design life is reached and it is considered for the analysis that a crack might initiate during the next starts of the machine.

3.3 New design life from reshaping

For both cases that indications were or were not found during an inspection, Fig. 4, it is recommended to investigate reshaping as a mid or long term repair solution of the generator pole fixation.
Reshaping describes the removal of the existing, fatigued and/or cracked material of the pole fixation, especially in the region of the highly stressed notches; see Fig. 5 and Fig. 6. The removed material is shown filled black. Up to a certain length cracks and the fatigued material can be removed by milling. The static strength assessment limits the allowed crack length, and therefore the maximum removable material. Furthermore, the new design can be stress reduced and the contact surface of the pole fixation can be evened for a better force distribution, especially for stacked components. Usually it is enough to remove relatively less material to reach good material. In this way, the life time of the component is reset after reshaping. The crack initiation process starts anew with the benefit of a stress reduced design.

The application range of reshaping is limited by the static strength assessment. The component must withstand the maximum static load with the required safety factor according to FKM-Guideline at the weakest cross section (see indicated by the blue line in Fig. 5 and Fig. 6). Therefore linear elastic and linear elastic ideal plastic 3D FEA are necessary. For the linear elastic ideal plastic 3D FEA the real material value of the yield point is used. Afterwards the fatigue strength assessment based on FKM-Guideline is performed for the new geometry. This assessment defines the maximum allowable load spectrum until a next inspection should be performed, similar to the assessment of the existing pole fixations.

The machining of the rotor and the poles can be done at site or at workshop.

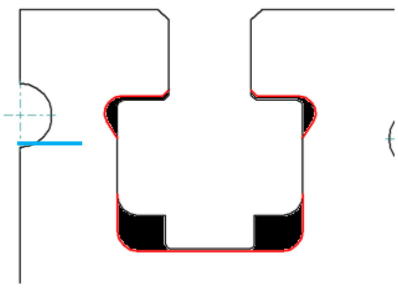


Fig. 5: Possible rotor rim reshaping geometry

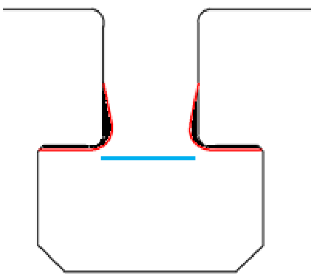
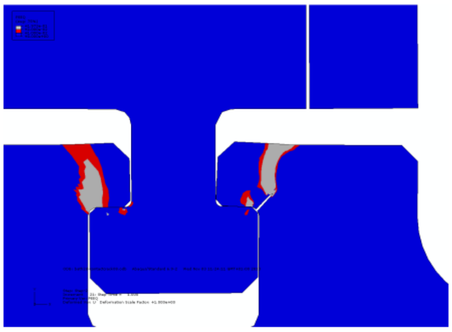


Fig. 6: Possible pole reshaping geometry

3.4 Remaining design life from fracture mechanics analysis

If long cracks are detected during an inspection and a reshaping is not applicable, the most appropriate validation of future operation is the crack propagation calculation. The generator pole fixation will be assessed in cooperation with an independent partner, experienced and qualified in fracture mechanics. The objective of this assessment is to define the maximum critical crack length of the components of the pole fixation. Therefore linear elastic and linear elastic - ideal plastic 2D FEA are necessary to define the crack tip load and the diffusion of the plastic zone (Fig. 7). Typically a safety margin is applied for the computation of the allowable crack size, as shown in Fig. 8. This calculation results in a number of additional start/stops until an inspection must be repeated. Within this timeframe a long term refurbishment or replacement of single components or machines can be investigated.



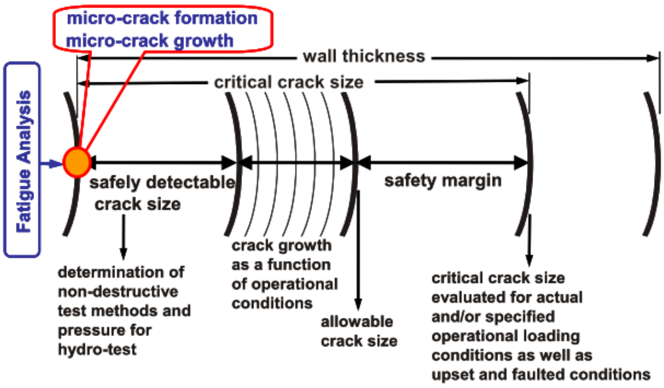


Fig. 7: Linear elastic - ideal plastic 2D FEA of the pole fixations for case study

Fig. 8: Scheme of the crack initiation and the crack propagation [2]

3.5 Remaining design life from fatigue assessment

In case the pole fixation is crack free after inspection and the minimum safety factor based on the FKM-Guideline is not reached yet, the remaining design life from the fatigue assessment defines the next inspection interval. The FKM-Guideline allows reducing the safety factor for NDT inspected parts by ~10% leading to an additional number of allowed load cycles until the design life is reached.

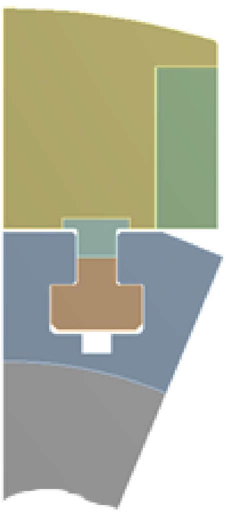
In case the pole fixation is crack free, but the minimum safety factor according to FKM-Guideline is reached, a possible next inspection can only be determined applying a reshaping or performing a fracture mechanics assessment.

4 Typical results of the assessment and subsequent works

An individual assessment for the repair solution is crucial for every project due to the design differences. The steps of the above described assessment process have been applied already to various projects. Some typical results are presented in the following paragraphs.

4.1 Typical FEA results

A typical project can have a pole fixation design with two 90° hammerheads. The CAD model set up for the 2D FEA is shown in Fig. 9. The results (Fig. 10) show high peak stresses in the notches of the pole fixation of rotor rim and pole. Furthermore the cut-out for the pole keys is highly stressed as well.



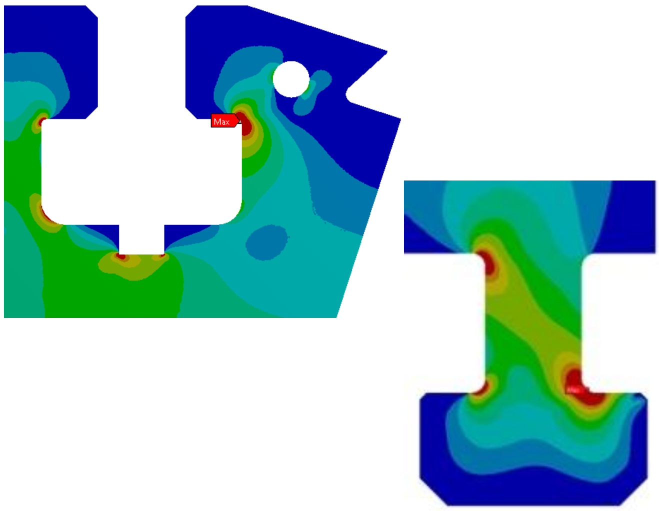
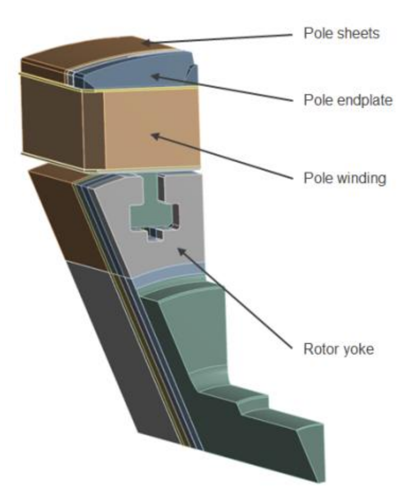


Fig. 9: 2D-FEA model

Fig. 10: 2D-FEA equ. v. Mises stress distribution

Fig. 11 shows a 3D model of a typical project. The highly stressed areas in the notches are clearly visible in the stress distribution of a 3D FEA as shown in Fig. 12.



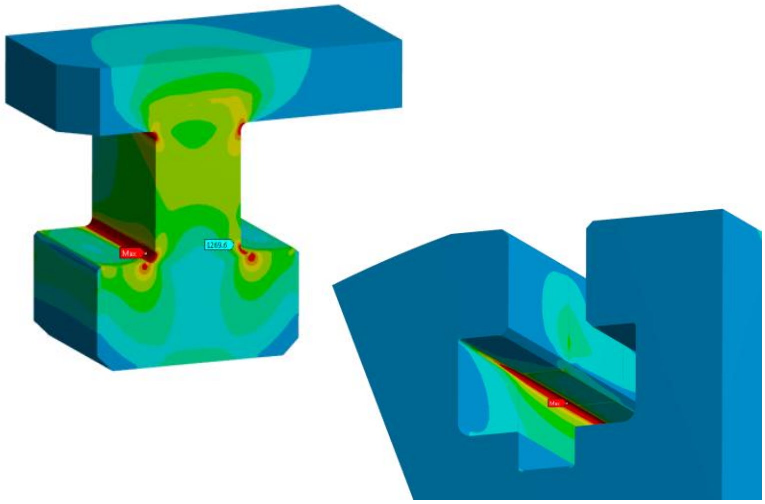


Fig. 11: 3D-FEA model

Fig. 12: 3D-FEA equ. v. Mises stress distribution

With results like this, a MT inspection of the pole fixation is highly recommended.

4.2 Typical inspection results

During an MT inspection typical indications can be found as shown in Fig. 13. Fig. 14 shows a typical excavated crack at the rotor rim, to define the maximum crack length.

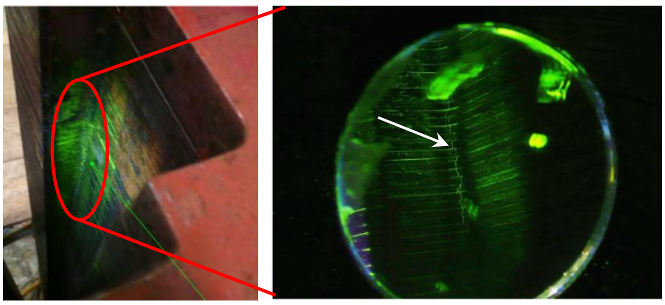


Fig. 13: Typical crack indication after grinding at the rotor rim area. Detail picture observed through a mirror.

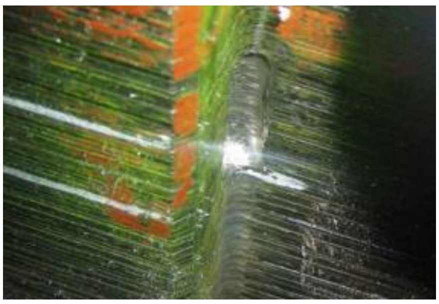


Fig. 14: Typical crack excavation in the rotor rim slot beside the contact area

A generator showing such results as in Fig. 13 and Fig. 14 should not go back in operation. For such a case, a repair or replacement solution for the machine or respective components can be developed and carry out in close collaboration with the owner.

4.3 Typical reshaping

Following pictures show examples of a typical reshaping work. Fig. 15 shows the original geometry before machining of the pole and rotor rim. The reshaping result is shown in Fig. 16.

Fig. 15: Original geometry of rotor rim and poles before reshaping from DE side

Fig. 16: Rotor rim slot and pole hammerhead after reshaping with adjusted pole key and air gap shim

The rotor rim itself was machined at three locations in parallel on site in the power house (Fig. 17). This led to a very short outage for the customer. The rotor weight was too heavy for transportation to the workshop. The rotor was machined on the contact surface and on the notches of the pole fixation. Additionally, the rotor key slot with sharp notches was removed.
Fig. 18 shows typical work set up for pole machining on a CNC machine in the company's workshop in Germany.

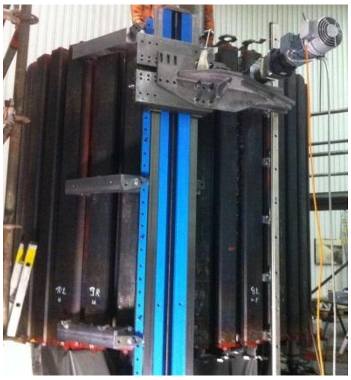


Fig. 17: Mobile machining of rotor rim at site

Fig. 18: Example of pole machining in the workshop of a typical project

For a typical project, such reshaping design can remove cracks up to a depth of few millimeters on the rotor rim and pole body. The removed crack size was limited by the critical cross section of the original design. The reshaping design ensures more than 40 years of safe operation for the customer, considering its daily operation behavior.

5 Conclusion

As a leading supplier of hydro power equipment, the company has been paying high attention to fatigue assessment of pole fixation. A procedure for the computational risk assessment including fatigue and residual lifetime has been established. Numerous generators worldwide have been already investigated. In a significant number of cases, where the strength assessment showed a risk, cracks on the pole fixation components were detected. For further operation of these generators additional measures like reshaping had to be carried out. All assessment and repair phases require a close collaboration with the customers in order to achieve a satisfying solution for the further operation of the electrical machines.
The experience outlined in this paper makes the company a reliable partner not only in the fatigue assessment of the mentioned hydro generator pole fixation, but as well in the transfer of the gathered knowledge to a successful solution for each electrical machine.

6 References

[1] **FKM Guideline**, Analytical Strength Assessment of Components, Forschungskuratorium Maschinenbau, 6th Edition, VDMA Verlag, 2012

[2] **E. Ross et al**, Design and Material Selection for Plants under Consideration of Fracture Mechanics Aspects, 35th MPA-Seminar, Stuttgart, 2009